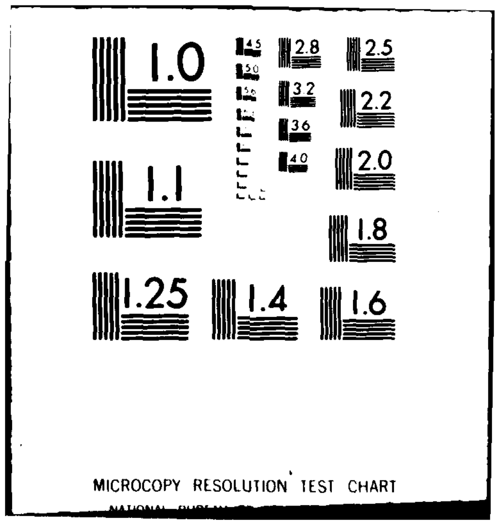
AD-A111 549 JOHNS HOPKINS UNIV LAUREL MD APPLIED PHYSICS LAB F/G 4/1
INFLUENCE OF METEOROLOGICAL PROCESSES ON THE VERTICALITY OF ELE--ETC(U)
JAN 82 M L HILL N00024-78-C-5384
UNCLASSIFIED APL/ATO-P/MLH82-06 ARO-14830.1-GS NL

END
DATE
FILMED
3-82
DTIC


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
MICROCOPY RESOLUTION TEST CHART

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER APL/ATO-P/MLH82-06	2. GOVT ACCESSION NO. AD-A111549	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Influence of Meteorological Processes on the Verticality of Electric Fields		5. TYPE OF REPORT & PERIOD COVERED Final Report Oct. 1, 1978-Sept. 30, 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) M.L. Hill		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Johns Hopkins University Applied Physics Laboratory Laurel, MD 20707		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS BH57-01
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE Jan. 15, 1982
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atmospheric Electric Fields, Mini Remotely Piloted Vehicle, Vertical Stabilization, Terrain Avoidance, Meteorological Sensing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A maneuverable atmospheric probe (MAP) was instrumented with atmospheric electric field sensors and operated at White Sands Missile Range to investigate meteorological affects on the verticality of electric fields. Verticality to within ± 2° was found to be the norm for fair weather conditions that included a high degree of convective instability. Near a large mountain peak, it was observed that the field contours are favorable for deriving information that is useful for preventing collisions of aircraft with mountainous and other terrain protuberances.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

INFLUENCE OF METEOROLOGICAL PROCESSES ON THE VERTICALITY OF ELECTRIC FIELDS

Abstract

A maneuverable atmospheric probe (MAP) was instrumented with atmospheric electric field sensors and operated at White Sands Missile Range to investigate meteorological affects on the verticality of electric fields. Verticality to within ± 2° was found to be the norm for fair weather conditions that included a high degree of convective instability. Near a large mountain peak, it was observed that the field contours are favorable for deriving information that is useful for preventing collisions of aircraft with mountainous and other terrain protuberances.

Results and Discussion

A method for obtaining a vertical reference for stabilization of airborne vehicles using the earth's atmospheric electric field was reported in 1972 (Ref. 1). In fair weather and some, but not all forms of adverse weather, the atmospheric electric field is oriented perpendicular to earth's surface. Under these conditions, a simple, solid-state electronic device weighing a few ounces and using a few milliwatts of power can be used as the vertical sensing components for an autopilot for aircraft.

Some research into the theory and operation of these devices was supported by DARPA in 1972-73 and by U.S. Army ERADCOM, Ft. Monmouth, in 1974 (Refs. 2, 3, 4, 5). The viability of the basic concept was demonstrated in flight tests of several mini remotely-piloted vehicles during 1974-1976 (Ref. 6).

Adverse weather phenomena such as thunderstorms, snow storms and some forms of frontal rainstorms cause disturbances of the usual verticality of the fair weather electric field. It is possible that methods might be developed to prevent malfunctioning of such stabilization units in some kinds of adverse weather, but it does not seem probable that methods can be developed to cope with all kinds of electric disturbances. Especially in the case of thunderstorm disturbances, the prospects for succes[illegible]ar bleak. Disturbances which prevent the use of the device, however, a[illegible]o be limited to about 10% of the earth's surface at any given time, or to 1[illegible] of the time at any one given location. Owing to climatology, conditions are probably favorable for a higher percentage of the time in some areas, whereas in others, the frequency and duration of disturbances may be greater than the nominal 10% value. In the desert regions of southwest U.S., we have found conditions to be favorable most all the time and we have conducted more than 150 flights of mini RPVs with this system in that environment.

To evaluate the usefulness and/or limitations of devices of this type, a need exists for investigations dealing with meteorological influences on the verticality of atmospheric electric fields. One of the objectives of this project was to attempt to investigate electric field characteristics through the use of a mini remotely piloted vehicle.

This research project was initiated in 1979 when the Applied Physics Laboratory was tasked by the Army Atmospheric Sciences Laboratory, White Sands, to develop a mini remotely piloted vehicle for the purpose of investigating meteorological parameters which affect the performance of electro-optical devices. The main effort dealt with turbulence measurements, aerosol and dust particle collection and other meteorological parameters. The atmospheric electric part of the work was sponsored by the Army Research Office.

The Maneuverable Atmospheric Probe (MAP) vehicle shown in Fig. 6 and 7 of an attached publication (Ref. 7) was constructed and first flown at White Sands, in August 1979. Some significant findings from flight tests carried out at WSMR and Maryland and are described in the attached reprint. In summary, a high degree of verticality (within ± 2°) was found to be the situation in fair weather conditions that included active convection capped with cumulus clouds. Other results described in the publication may have significant value in mini RPV surveillance, mini RPV systems that are to be fielded by the Army in the near future. These results deal with a demonstration that the curvature of electric fields near mountain peaks can be used to prevent aircraft and RPVs from colliding with such peaks.

Flight testing with this vehicle was interrupted in the fall of 1980 owing to curtailment of funds available from the Atmospheric Sciences Laboratory. It is hoped that the work can be resumed in the near future. A request for continuation of this project with ARO was considered, but has not been submitted because new clarification of ASL objectives or interest from other organizations would be needed to obtain a level of support that is commensurate with the task.

Publications and presentations derived from this project are listed below.

1. M.L. Hill, T.R. Whyte, R.O. Weiss, R. Rubio, M. Isquierdo, "Use of Atmospheric Electric Fields for Vertical Stabilization and Terrain Avoidance," AIAA Guidance and Control Conference, Albuquerque, N.M., August 19-21, 1981, AIAA Paper #81-1848-CP.

2. R. Rubio, M.L. Hill, H.N. Ballard, M. Isquierdo, C. McDonald, "The Maneuverable Atmospheric Probe (MAP), A Remotely Piloted Vehicle," Report #IRI-81-WS-113, Shellinger Research Laboratories, Dep't of Electrical Eng., Univ. of Texas at El Paso, 1981.

3. H.N. Ballard, M.L. Hill, M. Isquierdo, C. McDonald, R. Rubio, "A Remotely Pilited Maneuverable Atmospheric Probe," presented at American Geophysical Union Fall Meeting, San Francisco, Dec. 3-7, 1979.

4. R. Rubio, C. McDonald, "Remotely Piloted Vehicle Measurements of Met Parameters and Turbulence Structure Constraints," Presented at American Geophysical Union Conference, San Francisco, Dec. 37, 1979.

5. C. McDonald, M. Isquierdo, H.N. Ballard, R. Rubio, "Particulate Samples Collected with a Remotely Piloted Vehicle," Presented at American Geophysical Union Fall Meeting, San Francisco, Dec. 3-7, 1979.

6. H.N. Ballard, C. McDonald, M. Isquierdo, R. Rubio, and M.L. Hill, "Remotely Piloted Vehicle Measurements of Meteorological Parameters at North Oscura Peak, White Sands Missile Range, N.M.," Presented at American Geophysical Union Fall Meeting, 1981.

<u>References</u>

1. Hill, M.L., "Introducing the Electrostatic Autopilot," Astronautics & Aeronautics, Vol. 10, No. 1, November 1972, pp. 22-31.

2. Hill, M.L. and Hoppel, W.A., "Effects of Velocity and Other Physical Variables on the Currents and Potentials Generated by Radioactive Collectors in Electric Field Measurements," Proceedings of the Fifth International Conference on Atmospheric Electricity, Garmish-Partenkirchen, W. Germany, September 1974, pp. 238-248.

3. Hill, M.L. and Whyte, T.R., "Investigations Related to the Use of Atmospheric Electric Fields for Aircraft and RPV Stabilization," APL/JHU TG 1280, June 1975, NTIS A022051.

4. Leffel, C.S. and Hill, M.L., "Use of the Atmospheric Electric Field for Terrain Avoidance," APL/JHU TG 1271, March 1975, NTIS ADA-011830.

5. Hill, M.L. and Hoppel, W.A., "Comment on Wind Effects on Electrostatic Autopilots," AIAA Journal of Aircraft, Vol. 11, No. 12, December 1975, pp. 781-782.

6. Hill, M.L., "Design and Performance of Electrostatically Stabilized Delta Planform Mini RPVs," Conference Proceedings, Military Electronics Defense Exposition, Wiesbaden, Germany, Oct. 1977, Interavia SA, Geneva, Switzerland, pp. 847-861.

7. Hill, M.L., Whyte, T.R., Weiss, R.O., Rubio, R., and Isquierdo, M., "Use of Atmospheric Electric Fields for Vertical Stabilization and Terrain Avoidance," AIAA Guidance and Control Conference, Albuquerque, N.M., August 19-21, 1981, AIAA Paper No. 81-1848-CP.

Reprinted from CP815, A Bound Collection of Technical Papers

AIAA-81-1848-CP
Use of Atmospheric Electric Fields for Vertical Stabilization and Terrain Avoidance

M. L. HILL, T. R. WHYTE, R. O. WEISS,
R. RUBIO and M. ISQUIERDO

AIAA GUIDANCE AND CONTROL CONFERENCE

ALBUQUERQUE, NEW MEXICO
AUGUST 19-21, 1981

81-1848

USE OF ATMOSPHERIC ELECTRIC FIELDS FOR VERTICAL STABILIZATION AND TERRAIN AVOIDANCE

M.L. Hill,* T.R. Whyte,** R.O. Weiss,***
The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland

R. Rubio†
U.S. Army Atmospheric Sciences Laboratory
White Sands, N.M.

M. Isquierdo††
Shellinger Laboratories
University of Texas at El Paso
El Paso, Texas

Abstract

Using a light aircraft and mini-RPVs (remotely piloted vehicles), in-flight measurements of the quasi-electrostatic field which exists in the atmosphere have been made in various weather and terrain conditions. In fair weather, over flat terrain or rolling hills, the field vector is usually oriented within ±2° of a perpendicular to earth's average surface plane and, through the use of light-weight, low-cost voltage sensors, attitude reference signals can be obtained for vertical stabilization of aircraft. The stabilization system is operable in some but not all forms of adverse weather. Also, during flight tests of a mini remotely piloted vehicle near an 8000-ft high mountain peak, it was observed that favorable curvatures of the field lines exist and that such a stabilization system can provide for avoidance of collision with such protrusions. The heading of a mini RPV aimed towards the mountain peak was automatically changed to a heading directly away from the mountain by automatic commands generated by an electrostatic stabilization system. Signals in the roll axis loop of the electrostatic system show that in a region about 200 meters in front of a precipitous cliff the equipotential planes were favorably tilted downward to angles as large as 20 degrees. Some of the theoretical background is described and the use of the phenomena for terrain avoidance is discussed.

Introduction

An "electrostatic autopilot" was described by the first author in 1972.[1] It measures voltage differences between pairs of sensors located along the x and y axes of an aircraft as the aircraft maneuvers in the quasi-electrostatic field that exists between earth's surface and the ionosphere. The ionosphere typically is charged to about 350 kV positive with respect to earth. In fair weather and some forms of adverse weather, the electric field is usually oriented vertically to earth's surface and is the order of 100 to 200 V/m in the lower atmosphere. A relatively simple set of solid-state devices weighing 75 g with a power consumption of 50 mW can provide vertical stabilization.

Hill and Hoppel[2,3] discussed the physical and electrical processes that occur in the vicinity of the ionizing Polonium 210 alpha emitters commonly used for sensors. The processes involve aerodynamics and electrodynamics, so that the term electrostatic is inaccurate. Theories for and experimental verification of signal response as a function of aircraft velocity, intensity of the atmospheric electric field and radioactivity of the sensors were presented, and the effects of flight attitude, altitude, and field augmentation by structural geometry of the aircraft were discussed. This work was aimed at characterizing the relationships at low subsonic speeds.[2] Frierson et al. subsequently showed through tests of gun-launched projectiles that the attitude of small diameter rolling airframes could be sensed at supersonic speeds using similar devices.[4]

Some probable limitations on the usefulness of this device in adverse weather were recognized early,[1] but were not assessed quantitatively. Markson[5] provided a lengthy qualitative list of sources for distortion of electrical fields. Hill et al. subsequently operated mini-RPVs (remotely piloted vehicles) using this method of stabilization and made measurements using an instrumented light aircraft.[6-11] Their results are consistent with statistical analyses of electric field data, gathered at ground stations, which indicate that favorable electrical conditions can be expected to exist about 90% of the time on a global basis.

*Principal Staff, Aeronautics Division; Member AIAA

**Engineer, Aeronautics Division

***Engineer, Aeronautics Division, Member AIAA

†Research Physicist

††Research Engineer

Because of the emphasis on "all-weather" capability in most military hardware, serious considerations about using these devices for primary functions in tactical systems have been sparse. Their use thus far has been mostly as lightweight substitutes for vertical reference gyros in research programs where flights could be postponed if unfavorable electrical conditions existed. Much of our RPV testing has been done in Arizona and New Mexico, and postponements have been rare. Class et al. used electrostatic sensors to stabilize the PRAEIRE, which was the first mini-RPV to perform successful remote laser-designation missions for guided bombs and projectiles.[12] About one hundred stabilized flights were performed during the PRAEIRE Program. Lowe confirmed that the devices are entirely workable and he correctly pointed out that much remains to be learned about atmospheric electric phenomena and what limitations exist with regard to using electrostatic autopilots.[13]

On the basis of the physics of electric fields, it was predicted in Ref. 1 that this type of device could be used to assist in terrain avoidance navigation of RPVs. The expected favorable contoured equipotential surfaces near protrusions were described in a theoretical and experimental investigation reported by Leffel and Hill,[14] but actual tests of the concept were not possible until the summer of 1980, when the equipment and facilities needed to experiment with an RPV flying close to a mountain peak were finally assembled.

This paper describes results which show that field lines and equipotential planes in the atmosphere close to a mountain peak are curved in such a way as to cause an electrostatically stabilized RPV to steer away from such protrusions. It also describes the characteristics of electric fields in a region several miles distant from the same mountain, as well as in other regions where the electric field is useful for vertical stablization.

Discussion of Vertical Stabilization

In an effort to quantitatively measure electrostatic autopilot performance, personnel from APL fitted out the twin-engine Cessna Skymaster aircraft shown in Fig. 1 with apparatus that could be used to gather data about electric fields, atmospheric conductivity, local anomalies caused by weather effects, influence of aircraft self-charge and other factors. The key equipment included a two-axis vertical reference gyroscope, ten potential probes (polonium ionizers), associated electronics for measurement of vertical and horizontal voltage potential gradients, and a rotary field mill which provided a redundant check on the ionization probe equipment. Two types of instrumentation were used in conjunction with the ionzing sensors. One type was a specially constructed fast-response high-impedance (> $10^{14}\Omega$) voltmeter which measured potential differences in the atmosphere (often 1200 V).[8] The other was made up of simpler "low impedance" circuitry similar to that used for RPV autopilots. These latter circuits had 100 megohm input impedances and the terminology may seem confusing, but in relation to the very high impedance needed for true electrostatic measurements, calling them low impedance is correct. Apparatus was also included to adjust the self-charge potential of the airframe through a range of ±20 kV. A 24-channel, magnetic-tape data recording system was carried aboard the aircraft, and suitable computer techniques for data reduction and analyses were developed.[10]

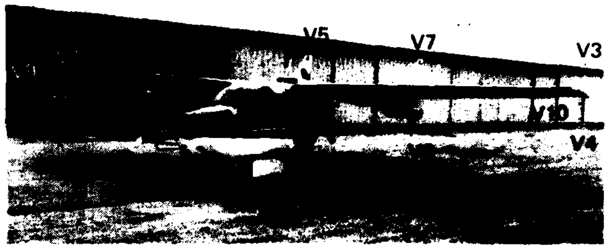


Fig. 1 Instrumented Cessna Skymaster used for investigations of atmospheric electric field.

Aircraft flying through snow, ice, rain and dust often take on large self-charge potentials because of triboelectric (frictional) charge separation.[15] Engine exhausts can also eject an excess of positive or negative ions,[16] thus raising the airframe to some potential above ambient. Self-charge on an airframe causes electric fields which interfere with making accurate measurements of atmospheric electric fields. The effects of such self-charge on the attitude sensing can theoretically be eliminated by locating the ionizers in regions having identical augmentation factors. In practice, it has been found that the symmetry of wing tips makes it relatively easy to arrive at roll sensing installations that are nearly immune to self-charge, but the lack of symmetry along the pitch axis causes some complications. No notable self-charging occurred with the Cessna Skymaster when flying in nonprecipitating weather but we observed some severe charging effects in rain and snow. Some satisfactory measurements of roll attitude were obtained in rain and light snow, but we were not able to carry to completion a program of definitive pitch measurements in precipitation before it became necessary to dismantle the equipment in the aircraft.

A typical set of measurements of the output of a high impedance sensing system as a function of bank angle during "S" turn maneuvers is shown in Fig. 2. The relationship is a sine function which can be described reasonably accurately with a straight line at small angles. The data of Fig. 2 were recorded during a fair mid-summer day with mild convective activity and about 30% cover of cumulus clouds with bases at 4500-ft (1372 m) altitude. No clouds were penetrated during this flight, but data passes at 4000 ft (1220 m) crossed underneath some clouds. Proportionality between bank angle and sensor voltage differences is clearly evident at each of the three altitudes of the data runs. The output per unit of bank diminished with increased altitude because the vertical potential gradient (VPG) decreased from about 150 V/m at sea level to about 35 V/m at 6000 ft (1830 m) on that particular day. This kind of variation of VPG with altitude arises from increased conductivity of the atmosphere and is the usual situation in fair weather.

Figure 2 shows that voltage differences as large as 800 V appeared between the sensors on the wing tips of this 11.6-m-span aircraft. Signals of this level are too large to use conveniently in autopilot loops and furthermore, the instruments are bulky and expensive. For this and other

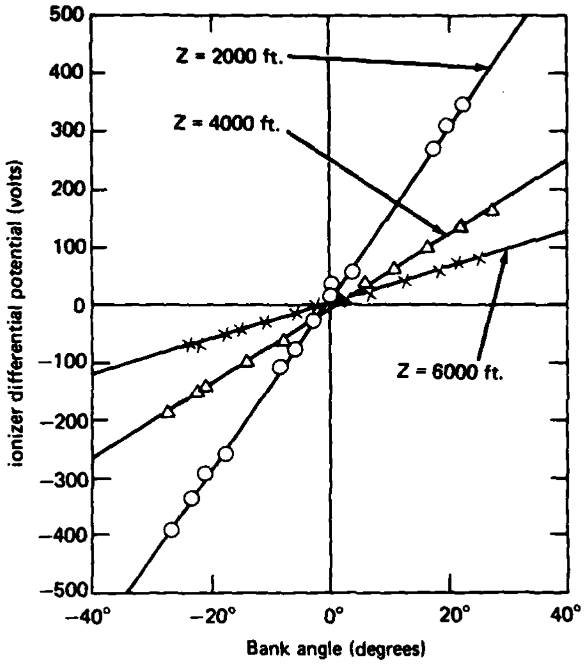


Fig. 2 Typical high impedance potential gradient sensor output during "S" turn maneuvers.

reasons, we employ low impedance systems in most of our RPV work. The performance of what we call low-impedance sensing systems is characterized by Figs. 3A-D. Figures 3A and 3B show the raw data from a vertical reference gyroscope and a (10^8 ohm) roll axis electrostatic sensor during a period when the Cessna was put through a double "S" turn having about 25° bank angles. Data of this type were analyzed to define quantitatively the vertical qualities of the electric field. The detailed method and computer program for this analysis are described in Ref. 10. The electrostatic sensor outputs were plotted versus bank angles as shown in Fig. 3C, which is similar to Fig. 2 except that sensor voltage differences are now in the range ±0.5 V instead of ±400 V. Numerous correlation plots were made to check the sensitivity of the two types of instruments and they have been shown to have a direct relationship to each other and to the VPG. In simple terms, the low-impedance autopilot circuits yield data of similar quality but with faster-response, lighter-weight, lower-cost instruments.

In Fig. 3C, only one out of ten of the digitized data points was plotted. The line through the points was computed by a least-squares method using all of the recorded data. From the intercept of this line at zero bank angle and from its slope at the same point, values were calculated for the voltage that should have appeared if the instruments had been perfect and if the electric field was in fact vertical in the region traversed during the data pass (~ 2 miles). Deviations of the individual data points from this "correct" value were then computed and plotted as in Fig. 4D. The maximum peak-to-peak values of deviations that occurred during the level portions of these data periods and additional periods of level flight during the next minute were used in conjunction with the slope and intercept of the "true" line to calculate the maximum errors in bank angle reported by the electrostatic sensors.

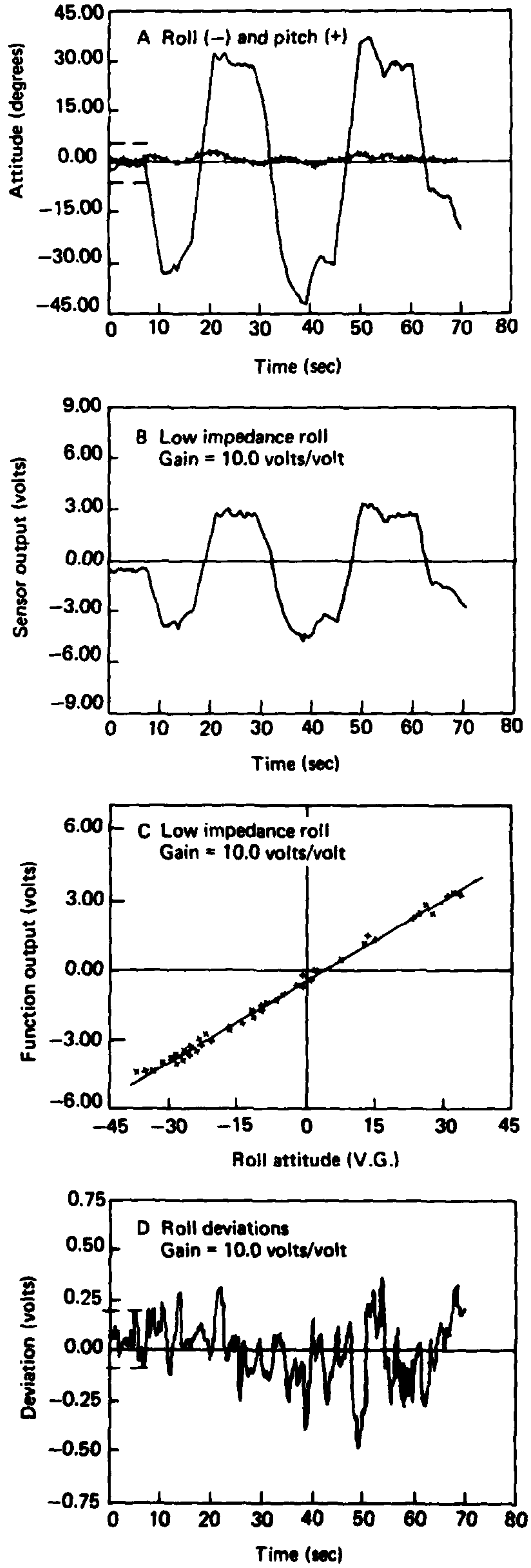


Fig. 3 Sample of low impedance electrostatic roll data used to determine maximum tilt of the atmospheric electric field vector.

The angles thus computed can be taken as representative of the maximum possible tilt angles of the electric field from vertical.

Deviations observed during essentially level flight were used for this analysis because there are other sources of excursions during sizeable maneuvers, such as unequal ionizer strengths, wing deflections, velocity gradients and sinusoidal outputs which have nothing to do with tilt of the earth's field. Especially on "bumpy" days, wing deflections caused deviations, and so did rocking of the gyro which was on a shock-mounted instrument rack. These factors were lumped in with the electrical data in estimating the maximum tilt angle of the electric field vector. Peak-to-peak values were used to calculate the "worst-case" tilt angles because we were seeking fine-scale effects that might be attributable to convection or turbulence. For use in describing the quality with respect to aircraft stabilization, (smaller) rms values would be more applicable.

Such "S" turn maneuvers were done periodically during a flight. Interspersed with these "S" turns, we would do a double roller-coaster pitch maneuver to about 20° of dive and climb. It was no joy ride for anyone susceptible to air sickness. Sometimes of necessity, but usually by design, we flew level for sustained periods between the roll and pitch maneuvers to record data about larger or longer term tilts of the field, as we will describe later.

Table 1 presents a typical set of fine-scale measurements made on a mildly convective but beautiful October day in Maryland. The estimated maximum tilt angle was ±4°, and the average was near ±1.5°. Also, the measurements by means of pitch maneuvers yielded substantially smaller tilt estimates than the roll measurements. We suspect this difference is associated with deflections of the wings and gyro mount but we have no way of being certain. Overall, the evidence is that the tilt angle was probably less than ±2°.

Table 1

Time	Altitude	Heading	VPG V/m	HPG V/m	Vector Tilt$_{max}$	Data Type
16:08	2000	10°	110	±4.5	±2.4°	Roll
16:22	4000	95°	100	±2.0	±1.2°	Roll
16:24	4000	285°	102	±2.8	±1.5°	Roll
16:24	4000	285°	102	±0.86	±0.5°	Pitch
16:38	6000	95°	90	±2.1	±1.3°	Roll
16:58	3000	170°	96	±0.78	±0.8°	Pitch
16:58	3000	170°	96	±2.6	±1.6°	Roll
17:09	3000	350°	92	±1.6	±1.0°	Pitch
17:13	3000	350°	88	±5.8	±4.0°	Roll
17:14	3000	95°	84	±2.0	±1.3°	Roll

VPG = Vertical Potential Gradient
HPG = Maximum Measured Horizontal Potential Gradient

A slightly different procedure was used to determine whether tilts occurred over larger distances (50-70 km) and altitudes than were traversed during these short burst pitch and roll maneuvers. For this purpose, zero intercepts of plots similar to Fig. 3C were determined over longer intervals using data recorded during essentially level legs of the flight. Mild "S" turns to about ±5° were inserted in these leg. to fix the slope of the line. The changes in the zero intercept voltage from its nominal value could then be taken as an indication of long-term tilts in the field vector. Data of this type are reported in Table 2.

Table 2

Long Term Measurement of Tilt of Atmospheric Electric Field

Time	Altitude Feet	Heading Degrees	Roll Intercept Volts	Tilt Angle
16:22	4000	95°	-0.3	-1°
16:24	4000	285°	-0.1	+1°
16:26	5000	95°	0.0	+2°
16:38	6000	95°	-0.4	-2°
16:41	6000	170°	-0.2	0°
17:13	3000	350°	-0.4	-2°
17:14	3000	95°	-0.4	-2°
17:25	2000	260°	-0.4	-2°

This flight was north and west of Frederick, Md., above the Appalachian Mountains some of the time but never at altitudes less than 1500 ft above the ridge peaks, which rise to 1800 ft in this area. From Table 2 it can be deduced that over this region during 1.5 hr we measured no tilts of the field larger than ±2°. Included in this value is a possible error of the same magnitude that was associated with temperature drifts of the electronics.

In addition to fair-weather flights, several flights were made during frontal rain storms, and one was carried out during a snow storm.[8-10] Some of the general conclusions are as follows:

a) On clear days (zero cloud cover), over flat terrain or rolling hills in rural areas, the atmospheric electric field is usually vertical to within ±2°, which was the limit of accuracy of our measurements.

b) Likewise, on days with convective activity that produces fair weather cumulus clouds, the field appears to be vertical within the accuracy of measurement at all altitudes between ground and cloud base.

c) Under non-precipitating cumulo-stratus clouds that typically precede the arrival of rain in frontal storm systems, the potential gradient at the ground is sometimes reduced to 20 to 30 V/m, compared to 150 to 200 V/m on fair weather days. Data gathered under these types of clouds indicate that the field vector was vertical up to cloud base.

d) Vertical fields were observed during some portions of a flight under precipitating clouds of a broad frontal rainstorm (a summer cold front in Maryland), but regions of nonverticality were observed near and in heavy-precipitation cells. These findings are considered only tentatively valid because some problems related to tribo-electric charging and short circuiting of the ion collectors interfered with the measurements.

e) Complete inversion of the electric field (negative upwards) was observed about 2.5 km from active thunderstorm cells. Reversals near thunderstorms are well known from previous literature. We have observed it many times on ground-based instruments and a few times with electrostatically stabilized RPVs as discussed below.

f) Reversal and severe tilting of the field was observed over Hanover, Pa., during a frontal snow storm. Between Frederick, Md. and Hanover (50 km), under a cumulo-stratus layer with light snow, the field was upright. A reversal and heavier snow occurred on the west edge of the town. East of the town, the field returned again to the usual positive upwards direction. It is not known whether this localized reversal (about 6 km wide) was related to charge separation in the snow clouds or to industrial pollutants rising from factories in the town. Other reversals have been observed on ground-based instruments during snow storms.

g) Near industrial smokestacks equipped with electrostatic precipitators, distortion and tilting of the field vector have been observed.[17] The extent of these disturbances is affected by meteorological conditions. On days with poor convective mixing and low wind we have observed effects that extended up to 1200 m altitude. On other occasions with moderate surface winds and weak convection, the effects were confined to altitudes below about 200 m.

Experience logged during several hundred flights of radio-controlled aeromodels and RPVs largely substantiates the measurements that have been made with the full-scale aircraft. Excellent stabilization is the norm for fair weather days. We have been able to fly in many more types of weather with our small vehicles than with the manned aircraft simply because they are less costly to operate and because there is no hazard to human life. For example, good stabilization occurred in ground fog when the visibility was about 250 m and also under and inside drizzling clouds having bases at less than 70 m above ground. We have often flown at less than 3 m above ground and have found that there are usually no untoward disturbances near the ground. Numerous automatic takeoffs and landings have been accomplished. We have tested vehicles under thunderstorm clouds (outside of the precipitation region) where the vertical potential gradient was 1500 to 2000 V/m and was reversed from the direction of polarity which is present during fair weather. Aircraft that were wired to stabilize in the upright position were observed to roll over, stabilize and fly in a straight path in the inverted attitude under the cloud.

A variety of remote missions were logged during flight tests of the APL-developed RPD-1 SYMDEL RPV at Ft. Huachuca, Arizona. This electrostatically stabilized aircraft, shown lifting off its launch dolly in Fig. 4, is spirally unstable and successful remote operation could not be accomplished without stability augmentation on the roll and pitch axes. Flights to 10 km ranged from the control station and to 9200-ft (2900-m) altitude (1550 m above ground level) were made. The weather at Ft. Huachuca during winter months provided useful electric fields nearly 100% of the time, day or night. Other tests were conducted during summer months when thunderstorms created inoperable conditions about 15% of the time. We learned that we could sometimes operate the RPV without trouble two miles from active thunderstorms and also that the electrostatic autopilot can cause an RPV to fly around, rather than penetrate a thunderstorm. Another delta, the RPD-2 Paradel shown in Fig. 5 was successfully operated at low altitudes over the brackish Potomac River at NSWC Dahlgren. This vehicle has a top speed of about 160 knots. Initially, there were problems related to velocity effects in loop gains, but these were resolved empirically in about 4 test flights.

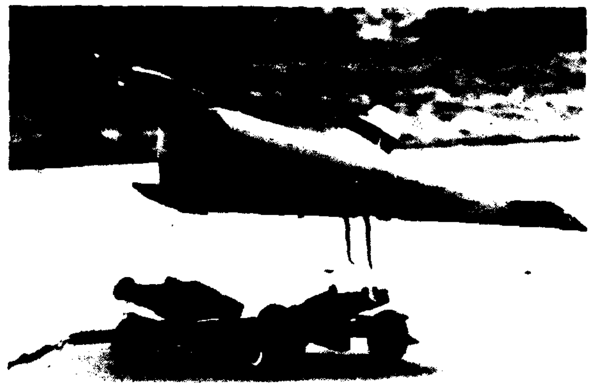


Fig. 4 RPD-2 Delta planform mini-RPV during launch at Ft. Hauchuca Arizona.

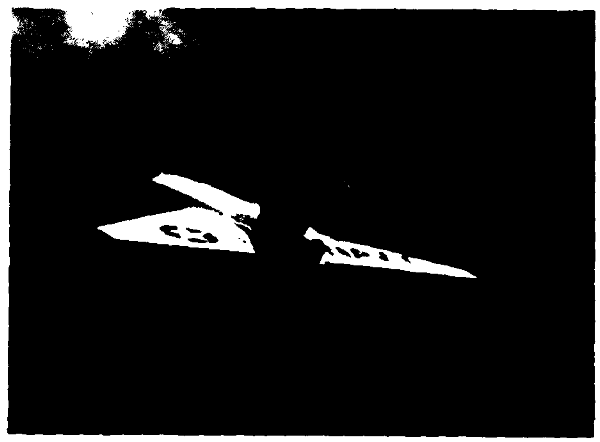
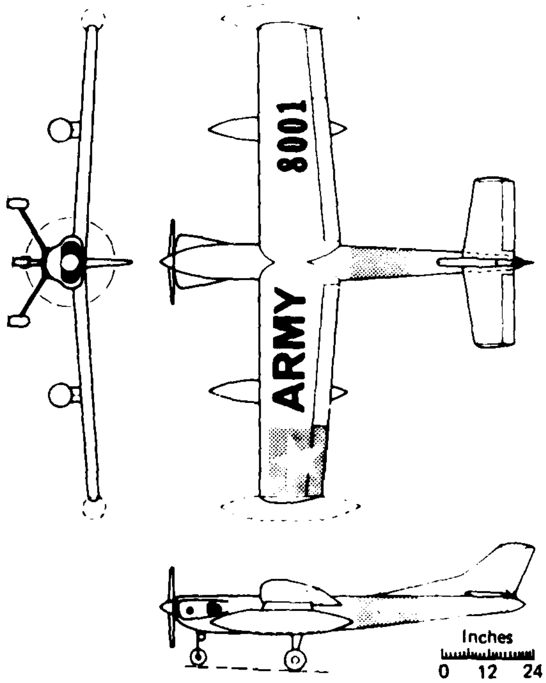


Fig. 5 RPD-2 Delta planform target during launch at NSWC, Dahlgren, Virginia.

In summary, it is clear that the electrostatic autopilot is not an all-weather device. However, these relatively simple and inexpensive devices could be exploited in expendable targets, training programs for RPV operators or other operations which can be scheduled to coincide with favorable weather. Additional research about the nature and duration of meteorological disturbances of the electric field will be needed to define whether they could be useful for vertical stabilization in tactical systems.

Discussions of Terrain Avoidance Experiments

In cooperation with the Army Atmospheric Sciences Laboratory at White Sands, N.M. and the University of Texas at El Paso, APL has recently developed an unusual and useful technique for meteorological research. The system includes a Maneuverable Atmospheric Probe (MAP), a mini-remotely piloted vehicle capable of carrying a 25-lb (11 kg) payload of meteorological sensors to altitudes up to 25,000 ft (7620 m). The main purpose of the work in this project has been to measure meteorological characteristics which affect the performance of electro-optical devices in the lower atmosphere. Some of the goals were that the vehicle and its operation should be low in cost, it should be operable in hazardous regions, (i.e., it has been flown 30 ft above exploding artillery shells) and it should be capable of slower flight and tighter maneuvers than is possible with manned aircraft so that fine-scale data can be gathered within small localized volumes of the atmosphere. The dimensions of the MAP vehicle are listed in Fig. 6. It is powered by a twin-cylinder, 2-cycle engine rated at 9 HP and has been flown at gross weights up to 96 lb (43 kg). Top speed at sea level is about 110 mph (175 kph) and minimum speed with its large flaps deflected is about 35 mph (56 kph). Two independent vertical stabilization systems were installed. One used a fluidic angular yaw rate sensor to provide wing levelling along with an angle-of-attack probe and rate damping gyro for pitch stabilization. The other stabilization method used a modernized version of the electrostatic pitch and roll attitude system described in Ref. 1.



Span	10 ft
Length	8 ft
Area	15.48 ft^2
Aspect ratio	6.46
Fuselage diameter	8.0 in.
Pod diameter	6.0 in.

Fig. 6 MAP vehicle.

The first tests of this meteorological sensing system were made in June 1979 at various locations above the relatively flat Tularosa Basin at White Sands Missile Range. No special data were acquired about the electrostatic autopilot. It was put on board mostly because we were confident that it would be usable for the planned work if a new and untested fluidic gyro system turned out to be unsatisfactory. Both systems performed well in workhorse fashion while we pursued the main objective of this program. In early July 1980, however, telemetry of the electric field sensors was functional when six data collection flights were made, again at W.S.M.R., but at a rustic site near North Oscura Peak which can be seen in the background of Fig. 7. This photograph of the MAP vehicle and a co-worker from W.S.M.R. was taken at a small dirt runway that had been graded in the foothills at 5800-ft (1768 m) elevation for this operation. Slant range from the runway to the top of the peak was about 1.3 mi (2 km).

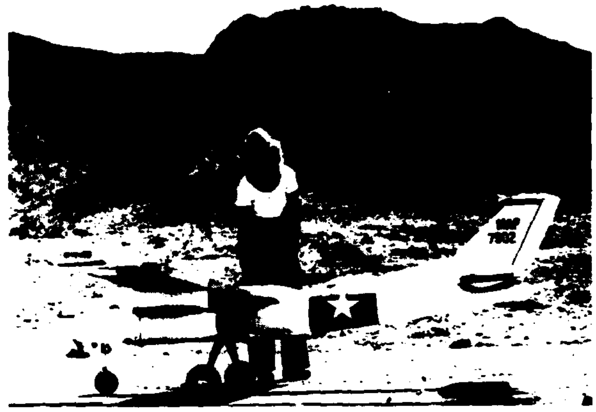


Fig. 7 Maneuverable Atmospheric Probe (MAP) at North Oscura Peak test site, White Sands New Mexico.

To orient the reader about the topography and probable contours of electric fields in the region of NOP we have constructed Figs. 8 and 9. Figure 8 shows results of a computation of the theoretical shape of equipotential contours around a 15-m-high wall of infinite length. The equations shown are a special solution to Poisson's equation for the potential ϕ for a case where λ, the atmospheric conductivity is assumed to be a simple exponential function of altitude, z. The value of λ near the earth's surface at sea level is typically 2×10^{-14} mho/m. The conductivity of the depicted wall was assumed to be infinite in comparison. Because of the large ratio of conductivity, field lines (which are perpendicular to equipotential lines) curve towards the protrusion and the field intensity is augmented at the top of the protrusion in a way that is analogous to the way that magnetic field lines are drawn into iron objects. The equipotential contours are highly curved close to the wall, but the distortion from their usual horizontal direction is no longer very severe at distances two to three scale heights in any direction away from the wall. Other solutions for protrusions such as fences, flag poles and mountains are shown in Ref. 14, as are experimental measurements which validate some of the theoretical solutions. Markson constructed a schematic diagram of the curvature of field lines near mountains which suggests the effects extend out to much greater heights and distances than we would expect on the basis of this kind of analysis.[5] Figure 9 is a schematic diagram which we believe to be representative of the atmospheric electrical situation near North Oscura peak. It shows an east-west vertical section of the terrain on a plane that slices through the surveyed reference point on the runway. The slice is, therefore, nominally along the line of sight to the peak as seen in Fig. 7. The terrain elevations were taken from a U.S. geological survey map and the mountain profile is accurate. The atmospheric electric field lines and equipotential planes are schematic constructions. Evidence for augmentation at the peak was, however, recorded on instruments that were located on the ground at the runway and at the mountain peak. Average values of the vertical potential gradient were 85 V/m at the runway and 210 V/m at the peak during the time of the tests to be described here.

The primary objective of this test series was to measure turbulence and gather dust and aerosol samples at altitudes up to 13K ft (4 km) and at distances from about one-tenth to three miles (0.2

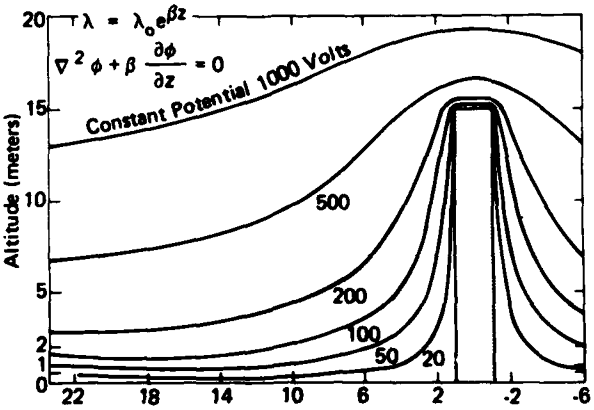


Fig. 8 Potential contours about a wall, 15 meters high in an atmospheric electric field of 100 V/m.

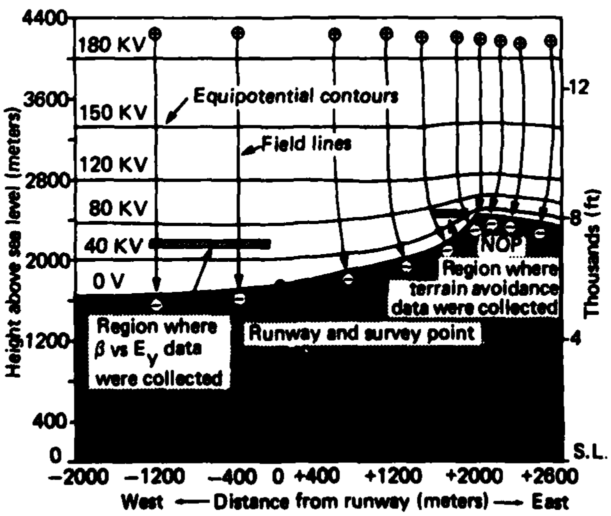


Fig. 9 Schematic diagram of equipotential contours and electric field lines in the vicinity of North Oscura Peak.

to 5 km) west of North Oscura Peak. During a brief portion of the last flight on July 10, 1980, special profiles were flown to record data for evaluating the performance of the electrostatic stabilization system in the vicinity of the peak and over the gently sloped valley to the west of the runway. For this operation, the take-off and climb-out were controlled by a pilot located on the runway. When the vehicle was midway between the runway and the peak, control was handed over to a pilot located at the top of the peak who could then keep visual contact while he steered the vehicle close to the peak. The vehicle was continuously tracked by a FPS-16 Radar and data printout was obtained listing its position, velocities, and accelerations in x, y, and z coordinates vs time.

The horizontal path during a 4.5-min period of flight at a nominal altitude of 7100 ft (2160 m) in a region above the sloping valley floor to the west of the runway is shown in Fig. 10. The aircraft was nominally level during the legs of the elongated loops to the west and northwest. Then it was flown around two circles to the left and two circles to the right at as steady a 30° bank angle as the pilot could hold visually. The electrostatic stabilization loop was engaged during this period and the circles were flown with the control stick nominally fixed so as to request a constant turn radius. Wind speed in the area at the time was low (3-5 knots) but there was convective activity and the pilot applied some small commands to attempt to keep the bank angle constant.

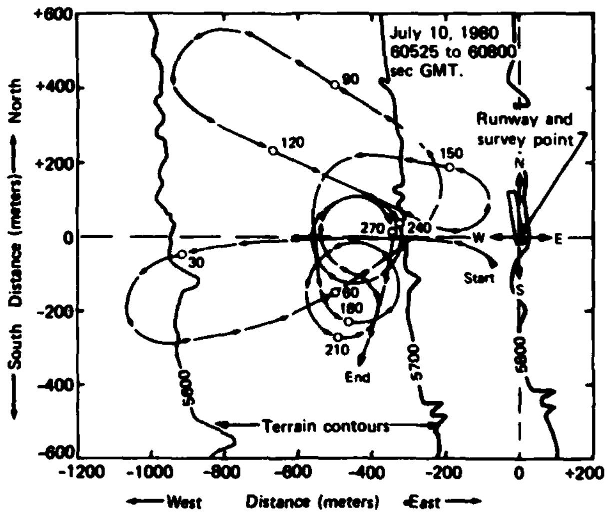


Fig. 10 Radar track of MAP vehicle during flight at 7.1 K feet altitude, about 1500 feet above gently sloping terrain.

Using the velocity and acceleration data reported in the radar data, calculations of bank angle, ϕ, were subsequently made using standard equations for the radius of fully coordinated turns. Some values for these computed bank angles are plotted against E_y, the roll axis output of the electric field sensors in Fig. 11.

On first inspection of Fig. 11, one might surmise that the electric field in the desert was of poorer vertical quality than it was over Maryland when the Cessna aircraft was operated in similar weather. Most of the scatter, however, probably arose from factors other than tilts of the electric field. For example, one frustrating extraneous problem was that the timing marks of the telemetry data tapes were offset by about 2-1/2 sec from those of the radar data. We were able to remove two seconds of the mismatch during data analysis, but there remains a mismatch of somewhere near 1/2 sec that could not be precisely determined or corrected. The MAP vehicle is capable of roll rates of up to 180°/sec, and it is probable that the actual bank angle at the instant of an E_y recording was often somewhat different from what it was 1/2 sec earlier when the co-plotted ϕ values (accelerations) were recorded by the radar. Also, some scatter doubtless appears on this figure because the radar track is oriented with respect to fixed spacial coordinates but the aircraft was actually maneuvering in light winds and convective turbulence. Data from a yaw probe showed evidence that this environment generated some spurious accelerations, but there was no way to assess them separately. For these reasons, values of E_y recorded during rapid changes in the direction or magnitude of accelerations were not plotted on Fig. 11. Still, the computed values for bank angles that are plotted here are probably nowhere near the quality of measurements that might have been obtained with a vertical reference gyro. They are, however, the only measurement method available to analyze these tests.

The above problems notwithstanding, there is, in Fig. 11, an obvious correlation between ϕ, the computed bank angle and E_y, the output of the electrostatic roll sensor. The nominal sensitivity is about 60 mV per degree of bank angle. We inspected the deviations from this straight line at the times the vehicle was on north, east, south and west headings during the circles and detected no correlation to heading. From this test, and also on the basis of many other flights of RPVs at Ft. Hauchuca in a nearly identical terrain situation, we tentatively conclude that there was no large tilt of the field vector over this valley. This conclusion conforms to the hypothetical contours of the equipotential surfaces sketched in this region in Fig. 9. Small tilts of the order of 2 to 3°, however, could have gone undetected.

Horizontal paths of the MAP vehicle during four passes made near the mountain peak for the purpose of examining the terrain avoidance capability of the electrostatic sensors are shown in Figs. 12A and 12B. The vehicle was flown at a nominal altitude of 8100 ft (2470 m), which was about 100 ft (30 m) above the peak, so that there would be space to recover control should anything be awry in the ideas being tested. A pilot, located at the point identified in the figure first steered the vehicle, with the wing leveler loop engaged, onto a course essentially parallel to the cliff face. When the heading was suitably aligned, the pilot removed his hands from the control stick and after 5-sec period of nominally straight flight he merely flipped a control switch that opened the gyro loop and engaged the electrostatic stabilization loop. The pilot also kept his hands off the

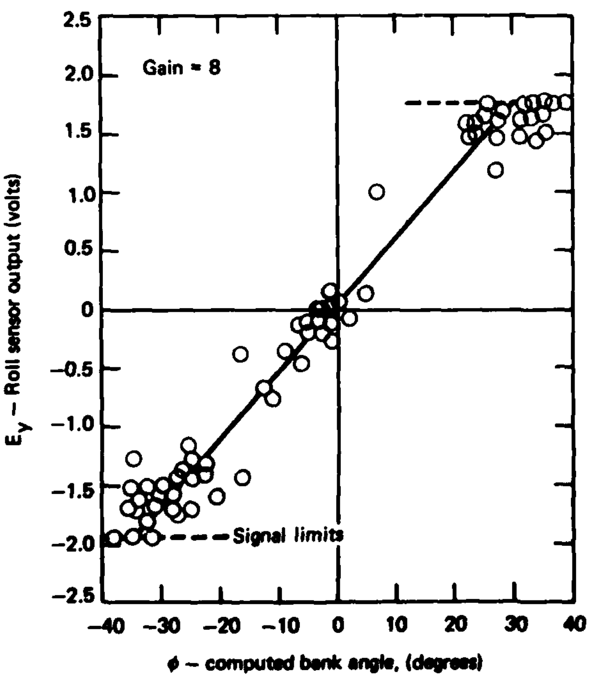


Fig. 11 Electrostatic roll output during level and circular flight paths about 1500 feet above gently sloping terrain.

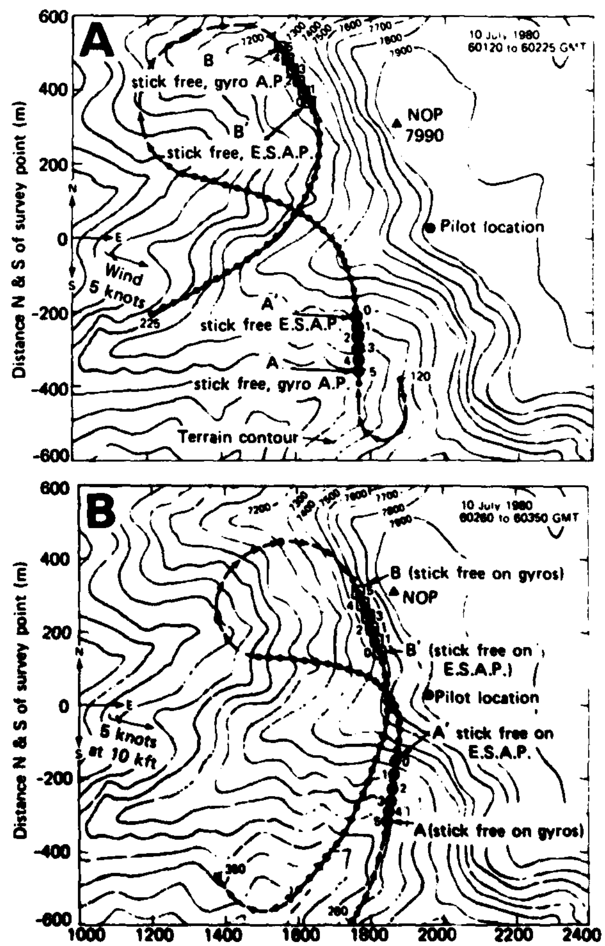


Fig. 12 Flight paths of MAP vehicle near North Oscura Peak.

control stick for the next 15 sec so that the path of the vehicle was certain to be affected only by its internals and mother nature's externals. The numbered open symbols of these figures represent a count-down during the 5-sec period of gyro control that preceded the transfer to electrostatic sensing.

From the radar tracks of the paths, it can be seen in Figs. 12A and 12B that the vehicle automatically veered away from the mountain when the electrostatic stabilization system was activated. Left turns to the west resulted during passes initiated on a nominally north heading while right turns to the west occurred during passes initiated on a southerly heading. Winds at the flight altitude were about 5 knots from the west and one would have expected the vehicle to drift to the east across the mountain peak, if it had been left to its whims on the wing leveler system. In hindsight, it is obvious we were being unnecessarily cautious in doing the passes at safe maneuvering altitude, for the turns away from the cliff were sufficiently sharp to have avoided a collision even if the vehicle had been as much as 100 m below the peak. In that region too, we would expect larger tilts of the field and still sharper turns.

We know of no extraneous forces other than electrostatic sensing that might have caused this autonomous behavior and, therefore, the radar-recorded flight paths are fairly conclusive evidence that the principles discussed in Figs. 8 and 9 are valid. In an effort to verify the electrostatic effects quantitatively, however, a special examination was made of the electrostatic signals during the maneuvers close to the peak. In Figs. 13A and 13B the values of E_y that were generated by the electrostatic roll sensor are plotted against the computed bank angles for the 20-sec period of each of these four data runs. Again, open squares and circles represent data recorded during the five second count-downs of wing leveler control, and crossed symbols denote data points taken after the electrostatic loop was engaged. This figure has coordinates identical to those of Fig. 11, and the dotted line represents E_y vs ϕ when the electric field was vertical (or nearly so) over the valley floor. Again there is scatter of the data for the same reasons discussed previously. In both figures and for all four runs, however, the trends are identical. There was a biased output while the vehicle was flying parallel to the ridge on the wing leveler (open symbols joined by arrows) and there was essentially zero output (crossed symbols) even though the aircraft assumed bank angles as large as ±20° during the electrostatically controlled turns away from the mountain. The initially biased signals are presumably the result of a winge-level attitude and a tilted field. Then, because the electrostatic stabilization loop is set up to produce turn commands until the voltage difference across the sensors is zero, the aircraft banks to hold its wing tips on the local contour line of the tilted equipotential planes when the electrostatic loop is closed. For clarity, and because it would represent a mixture of three variables simultaneously (time, bank angle and local tilt of the electric field), we have not drawn a line through the crossed points of Fig. 13A and 13B. But had we done so, the line would be essentially horizontal at zero volts. A series of near zero values occurs throughout the turn because both the bank angle and tilt of the field decayed to zero as the vehicle traveled away from the mountain. The largest bank angles reached during the period when the output was near zero were of the order of ±20°. They occurred almost immediately after the electrostatic loop was engaged. From this, we deduce that the equipotential surfaces were tilted to as much as 20° downward and away from the peak in some of the regions traversed during these passes.

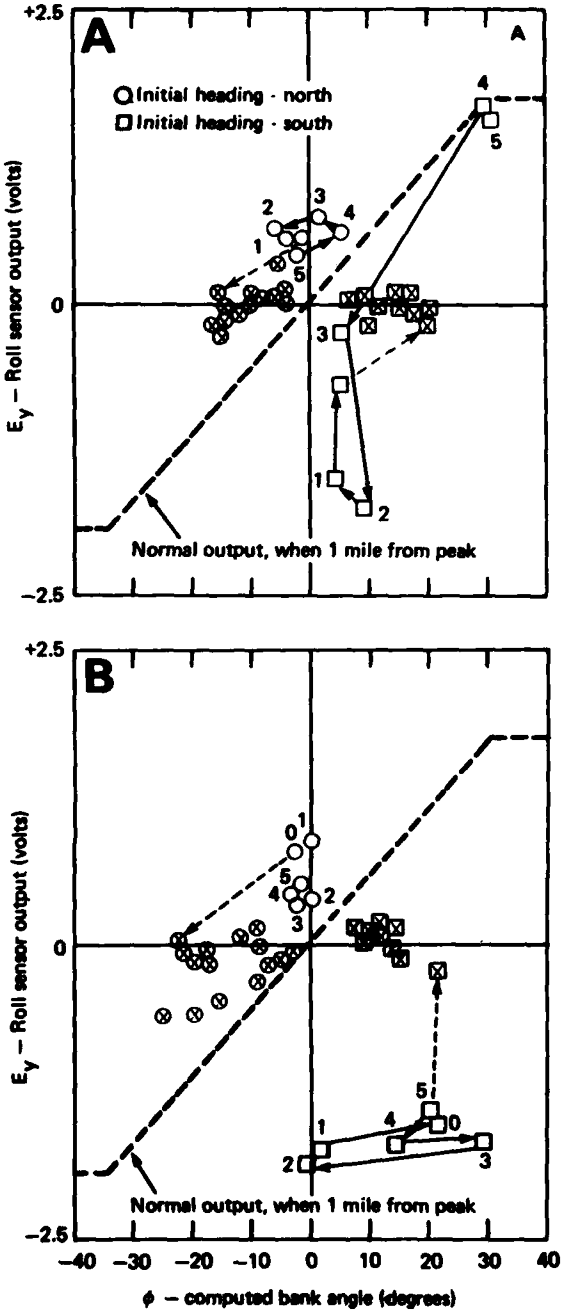


Fig. 13 Electrostatic roll output in close proximity to a mountain peak.

There are sound reasons to expect that if an aircraft with the speed and maneuverability characteristic of the MAP were aimed on a course perpendicular to and toward such a cliff face at altitudes below the peak, the aircraft would automatically pitch up and turn onto a course away from the mountain face before it got within 200 to 300 m of the mountain face. Such a display would have been more dramatic than the tests described here, but it was deemed wise not to do it until after a more quantitative map of the field vectors in a larger region around such a mountain has been acquired. It is hoped that suitable equipment can soon be added to the MAP vehicle and that flights for this purpose can be resumed.

It is possible to envision a variety of ways in which the terrain avoidance features of electrostatic stabilizers might be used. As an example, one can envision its use as an auxiliary sensor for remotely piloted vehicles or autonomous drones intended for use in mountainous regions, an environment where typical drift errors in inertial navigation equipment or in radio navigation systems could be large enough to allow collision with such protrusions. Additionally, such a sensor could detect and provide means for navigation around down-range thunderstorms. More must be learned, however, about the basic phenomena and weather effects to make valid judgment about the applicability of such devices for specific drone systems and missions.

Acknowledgments

The Army Research Office, Durham, N.C. provided a portion of the support for this work and the authors are grateful to Dr. A. Dodd and Dr. Leo Alpert of that office for their interest. Other support came from the U.S. Army Atmospheric Sciences Laboratory and the special organizational efforts of Dr. Henry Rachelle and Mr. Harold Ballard of that laboratory were very helpful.

At the Applied Physics Laboratory, Messrs. Robert Lee, Melvin Newcomer, William Charbonneau and Michael DeMuth made valuable contributions to the development of flight hardware. Luigi Perini formulated the computer programs and plotting methods used for examination of the MAP flight data and Mrs. Lillian Goldfinger patiently helped with the manuscripts and organizational problems. Assistance from Dr. Carlos McDonald and Messrs. Carlos Herrera and Luis Alphonse Yip of University of Texas at El Paso is also greatly appreciated, as is that from Mr. Claude Tate and Ms. Margaret Boyett of White Sands Missile Range.

References

1. Hill, M.L., "Introducing the Electrostatic Autopilot," Astronautics & Aeronautics, Vol. 10, No. 1, November 1972, pp. 22-31.

2. Hill, M.L. and Hoppel, W.A., "Effects of Velocity and Other Physical Variables on the Currents and Potentials Generated by Radioactive Collectors in Electric Field Measurements," Proceedings of the Fifth International Conference on Atmospheric Electricity, Garmish-Partenkirchen, W. Germany, September 1974, pp. 238-248.

3. Hill, M.L. and Hoppel, W.A., "Comment on Wind Effects on Electrostatic Autopilots," AIAA Journal of Aircraft, Vol. 11, No. 12, December 1975, pp.781-782.

4. Frierson, J.L., Moore, F.G., and Van Meter, R.L., "An Electrostatic Roll Sensor for Supersonic Vehicles," AIAA J. of Aircraft, Vol. 15, No. 4, April 1978, pp.195-198.

5. Markson, R., "Practical Aspects of Electrostatic Stabilization," AIAA Astronautics & Aeronautics, Vol. 12, No. 4, April 1974, pp.44-49.

6. Hill, M.L. and Newcomer, M.R., "Flight Tests for Evaluation of Gust Disturbances and Control Responses of a Delta Planform Mini-RPV (Remotely Piloted Vehicle)," APL/JHU Report, BAF-76-05, March 1976.

7. Jarvinen, P.O. and Bruce, C., "Mini RPV Flight Dynamic Measurements," Proceedings of AIAA Conference on Guidance and Control, San Diego, Calif., August 16-18, 1976.

8. Hill, M.L. and Whyte, T.R., "Investigations Related to the Use of Atmospheric Electric Fields for Aircraft and RPV Stabilization," APL/JHU TG 1280, June 1975, NTIS A022051.

9. Whyte, T.R., "Preliminary Report on Atmospheric Electric Field Research Program for April, May and June, 1975," APL/JHU Report BAF-75-07.

10. Hill, M.L., Weiss, R.O. and Whyte, T.R., "Investigation of the Use of Atmospheric Electric Fields as a Vertical Reference for Airborne Vehicles," APL/JHU Report NO. BAF-76-20, September 1976.

11. Hill, M.L., "Design and Performance of Electrostatically Stabilized Delta Planform Mini RPVs," Conference Proceedings, Military Electronics Defense Exposition, Wiesbaden, Germany, Oct. 1977, Interavia SA, Geneva, Switzerland, pp. 847-861.

12. Class, J. and Cochran, S., "Praeire Mini RPV System," Proceedings of the NATO Conference on Remotely Piloted Vehicles, Milan, Italy, September 1976.

13. Lowe, D.T., "Mini RPV Technology Development," Unmanned Vehicle Systems Magazine, Winter Issue, 1979.

14. Leffel, C.S. and Hill, M.L., "Use of the Atmospheric Electric Field for Terrain Avoidance," APL/JHU TG 1271, March 1975, NTIS ADA-011830.

15. Gunn, R., Hall, W.D. and Kinzer, G.D., "The Precipitation-Static Interference Problem and Methods for Its Investigation," Proceedings I.R.E. and Waves and Electrons, April 1946.

16. Imyanitov, I.M., "Aircraft Electrification in Clouds and Precipitation," Foreign Technology Division, Wright Patterson AFB, NTIS Document AD 726-581, 1971.

17. Hill, M.L. and Whyte, T.R., "Remote Detection of Chimney Plumes by Means of Atmospheric Electric Fields," Proceedings of the 4th Joint Conference on Sensing of Environmental Pollutants, American Chemical Society, 1978, pp. 566-571.